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Space Shuttle Pogo Pressure Measuring System A Progress Report

John S. Hilten and Paul S. Lederer

Electronic Technology Division
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

July 15, 1974

Progress Report Covering Period
January 15, 1973 to September 15, 1973

Prepared for

NASA George C. Marshall Space Flight Center
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This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in the final report. Performance Test Data were obtained from one or two samples of several transducer types, and do not necessarily represent the characteristics of all transducers of a given type.

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

ABSTRACT

This progress report describes a variety of experimental approaches to the dynamic calibration of pogo pressure transducers for the measurement of oscillatory pressures generated in the propulsion system of the space shuttle. The requirements are for the generation of a known (5% or better) sinusoidal pressure perturbation of 140 kPa (approx. 20 psi) peak-to-peak at bias pressures up to 55 MPa (8000 psi) over a frequency range from 1 Hz to 100 Hz. Vibrating a liquid column in a vertical plane is one technique developed that achieves 53 kPa (7.7 psi) peak-to-peak from 30 Hz to 150 Hz at all bias pressures, with smaller amplitudes at lower frequencies, reaching about 6 kPa (0.9 psi) peak-to-peak at 10 Hz. Another technique, rotating a liquid column in a vertical plane, shows promise at frequencies from 10 Hz down.

KEY WORDS

Calibration; differential pressure; dynamic; high pressure; orbiter vehicle; pogo; pressure; sinusoidal; space shuttle; transducer.

Space Shuttle Pogo Pressure Measuring System

Progress Report for the Period
from January 15, 1973 to September 15, 1973

to the

George C. Marshall Space Flight Center
NASA Order #H-92100A
NBS Project 4253448

Prepared by

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and
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1. Introduction

The objectives of this project include the development of a dynamic pressure calibration technique for pogo pressure transducers, for the measurement of oscillatory pressures generated in the propulsion system of the space shuttle and the evaluation of several commercial transducers for suitability for the measurement of these pressures. The requirements for this measurement specify a full-scale range of 140 kPa (approx. 20 psi) [1] peak-to-peak at bias pressures up to 55 MPa (approx. 8000 psi) over a frequency range from 1 Hz to 100 Hz. Propulsion system temperatures in the space shuttle are expected to range from about -253°C (-425°F) to about 482°C (900°F); the transducers used for the pogo measurements will be required to operate at some temperature within that range, depending on the final choice of their location within the propulsion system of the space shuttle orbiter vehicle. The definition of objectives will be suitably modified at a later date to establish the actual operating conditions for these transducers.

The current project efforts are directed toward the development of a dynamic pressure calibration technique suitable for use at ambient laboratory temperature, the procurement of promising commercial off-the-shelf (or suitably modified) transducers, and the evaluation of such transducers. A dynamic pressure comparator is under development by the Cryogenic Metrology Section of NBS Boulder to make it possible to compare the response of a pogo pressure transducer at cryogenic temperatures with the response of a similar transducer at laboratory ambient conditions.

2. Development of Dynamic Calibration Techniques

[1] 1 kPa = 0.145 psi, 1 MPa = 145 psi
[2] See Reference 1

As indicated in the previous progress report [1], feasibility has been demonstrated of a calibration procedure which subjects pressure transducers to sinusoidal pressure variations at amplitudes ranging up to 53 kPa (7.7 psi) peak-to-peak, and at frequencies from 10 Hz to 150 Hz in the presence of bias pressures from 0 to 55 MPa (0 to approx. 8000 psi). The procedure, which involves a liquid-filled tube mounted on an electrodynamic vibration exciter (see Figure 1), does not extend to the desired low-frequency limit of 1 Hz. Subsequent efforts described in this report have largely been directed towards extending calibration capabilities to lower frequencies. In addition, certain problems encountered with the above technique were investigated, and further work was done on a technique involving a double-ended piston-cylinder driven by a vibration exciter.

There were three problems with the liquid filled tube calibration system: (1) The halving of the generated pressure amplitude when the tube is capped to superimpose a bias pressure with the consequence that either the tube height, the liquid density, or the applied acceleration must be increased to obtain the same pressure, (2) observed inconsistencies in generated pressure amplitudes with variations in bias pressure up to 14 MPa (approx. 2000 psi), and (3) the inability to cover the lower frequencies (1 - 10 Hz) because of displacement limitations of available vibration excitors: for instance, to achieve even 20% of the specified 140 kPa (approx. 20 psi) peak-to-peak pressure at 1 Hz would require 5.3 m of displacement using a 32-cm column of oil, and 0.3 m of displacement with a mercury-filled tube.

In the case of the double-ended piston-cylinder calibrator, frequency response capability, bias pressure capability, and modulation pressure considerations looked promising in preliminary experimentation, but the apparent sensitivity of the transducer calibrated with it, as determined from calculations using the test data, was only about 40% of the predicted value in a number of tests.

In this report work done along these two calibration approaches and four additional calibration approaches will be described.

2.1 Liquid Filled Vertical Tube Calibrator

2.1.1 Pressure Halving In Closed Tubes

The halving of the pressure amplitude generated with the closed tube relative to the open tube is explained by the following considerations: In the open tube, the upper surface of the liquid is unconstrained and hence is the locus of a pressure node. At the lower end of the tube the velocity is constrained to be zero (in the acceleration frame of reference) and acceleration (and hence pressure) is a maximum. Pressure is proportional, therefore, with distance from the node (open end). When the tube is capped, the upper surface of the liquid is, like the lower surface, constrained to zero velocity

(again in the acceleration frame of reference) and equal pressure maxima occur at the ends. From symmetry considerations, it can be seen that the pressure node must be located halfway between the ends so that the pressures in the liquid column will range from zero at the center to equal maxima, determined by the acceleration amplitude, at the ends. These maxima, however, created by the liquid "Head" over one-half of the tube length, are then only one-half of the value for the open tube. The same considerations lead to the doubling of resonance frequency of the closed tube system relative to the open tube.

To confirm our understanding of the halving of the generated pressure amplitude in a capped or closed system, a new tube was fabricated in which the transducer was mounted 12 cm from the bottom of a 31-cm tube (about 40% up from the bottom of the tube). Calibrations were performed with the tube capped and with the tube open. The test was repeated with the transducer 6.1 cm from the bottom of the tube (about 20 % up from the bottom of the tube). The experimental data indicate, as expected, that when the tube is open the dynamic pressure level is determined by the height of the liquid column above the center of the transducer multiplied by the density of the liquid and by the shaker acceleration level. When the tube is capped, however, the dynamic pressure level must be calculated by measuring height from the <u>mid point</u> of the entire liquid column to the center of the pressure transducer. The transducer mounted at a point 40% from the bottom of the tube sees six times the pressure in the open tube that it sees in the closed tube. Figure 2 shows the data in graphical form for Transducer A-3. The expected doubling of natural frequency for the capped tube system was also observed.

2.1.2 Data Variation Due to Voids in Liquid-Filled Tubes

In many previous tests performed at bias pressure levels up to 14 MPa there was a considerable scatter in data. It is now clear that considerable care must be taken to see that the capped tube does not contain a void. If this condition exists, the generated pressure at the bottom of the tube can vary anywhere from that in an open tube to the half pressure (see previous discussion) generated in a completely filled tube. Even when the tube is properly filled, care must be taken at low bias pressures. It can be seen, for instance, that with zero bias pressure in a capped tube which is properly filled, a slight change in temperature will produce either a positive bias pressure or a cavity due to unequal expansion or contraction of liquid and tube. The warmth generated by holding the tube in one's hand for a two-minute period was sufficient to drive the bias pressure up approximately 340 kPa. As will be pointed out in a later section, the liquid-filled system resonance frequency has been observed to be a smooth function of the pressure in the tube; this variation in resonance can be used to monitor bias pressure readily to within an estimated ±170 kPa.

In an experiment where 6.89 MPa bias pressure was applied to a properly filled and capped tube and then reduced in successive steps to 6.21, 5.52, 4.83, 4.14, 3.45, 2.76, 2.07, 1.38, 9.69, and 0.21 MPa the total transducer sensitivity variation at 50 Hz was within 1.5%, well within the estimated limit of error for the calibration. Table I shows the values of sensitivity and resonance frequency as a function of bias pressure. The transducer tested was Transducer A-3.

2.1.3 Transducer Response as a Function of Bias Pressure 15-150 Hz

A new calibrator tube was fabricated to permit the simultaneous calibration of two pressure transducers. It is shown in Figure 1. In this calibrator each transducer under test is mounted flush in each of two flat steel plates, 4.1 cm square and 0.95 cm thick. These plates in turn, are fastened with four bolts to machined flats on opposite sides of the block holding the vertical liquid-filled tube. The seals between plates and flats are achieved with metal seal rings.

Transducers A-1 and A-2 were calibrated simultaneously in three consecutive calibrations at bias pressures ranging from 6.9 to 55 MPa over a frequency range from 15 to 150 Hz and at pressure levels up to 55 kPa peak-to-peak. These calibrations were performed at laboratory ambient conditions. No sealing tape was used for the transducers.

Representative values of sensitivity for the transducers at 6.9 MPa bias pressure, 50 Hz, are 3.98 mV/kPa for transducer A-1, and 3.71 mV/kPa for transducer A-2 (27.1 mV/psi and 25.7 mV/psi respectively). These measured sensitivities over three calibrations show a spread of 0.37% for A-1 and 0.68% for A-2. Sensitivity values at pressures from 6.9 MPa to 55.2 MPa show a spread of 3.9% and 1.8% respectively. Our calibrations have an estimated total error of $\pm$3.80%, consisting of an estimated total systematic rms error of $\pm$1.85% plus three times an estimated total random rms error of $\pm$0.65%. Table 2 shows a tabulation of the data while figures 3 and 4 show the data graphically. Table 3 is a compilation of the sources of error of these calibrations, performed in the NBS transducer laboratory.

When the tube, liquid height and temperature are unchanged, the resonance frequency of this system is observed to be a smooth function of the bias pressure, as shown in Figure 5. The value of resonance frequency is thus a sensitive indicator of changes in the value of bias pressure resulting from leakage or temperature change. It is estimated that a change of $\pm$170 kPa can be detected. This change in resonance frequency with bias pressure can not be accounted for wholly by the change in liquid density (and thus the speed of sound in a liquid); it is possibly a function of tube geometry.

It is planned to use this particular calibrator for the dynamic calibration of all test transducers in the range from 10 Hz to 150 Hz. To cover the low-frequency region between 10 Hz and 1 Hz, we are in-

vestigating several schemes, of which the following one appears most promising.

2.2 Low Frequency Calibration Techniques

2.2.1 The "Windmill" Calibrator

A brass tube, 1.6 cm inside diameter, and 2.2 cm outside diameter, and 38 cm long, plugged at both ends, was attached to a similar tube by means of a stud to make a 76-cm long structure. Transducer A-3 was then mounted in the end of one of the tubes after it was filled with 35.6 cm of oil; this left an air gap of about 2.5 cm. The other end of the structure was provided with an adjustable screw that was used for balancing purposes. The 76-cm structure was then mounted at the end of a shaft that lies in a horizontal plane so that as the shaft rotates, the 76 cm long structure rotates in a vertical plane. See Figure 6. This shaft, supported on air bearings, equipped with slip rings, and driven by a low-speed motor, is part of the prototype Earth's Field Dynamic Calibrator for Accelerometers [3] developed by this laboratory.

During rotation the pressure developed at the diaphragm of the pressure transducer at any constant rotational speed (frequency) is composed of both a static and a gravity component. The peak-to-peak amplitude of the gravity component is computed from the height and density of the liquid column multiplied by 2; the static, or steady state, component is determined by the centripetal force as measured at the center of the oil column and density of the oil. A correction must be made for a transducer that responds to static pressure, but for a piezoelectric transducer no correction is necessary.

Using this apparatus, transducer A-3 was calibrated from about 2 Hz to 9.5 Hz, and then the transducer tube was removed and remounted on the shaker for a liquid-filled-tube calibration from 10 Hz to 150 Hz. The two calibration methods agreed to within 1% at the junction of the two sets of data. The dynamic pressure level was 5.9 kPa peak-to-peak; no bias pressure was used in this test. The 3-dB down point was extrapolated to be at 1.42 Hz. Figure 7 shows the data graphically with the sensitivity at 25 Hz assigned a response ratio of 1.0.

In a similar experiment, but using a shorter tube, the oil was replaced with mercury to generate a nearly sixteen-fold increase in pressure range. While this was a preliminary investigation covering only a frequency range from 2 Hz to 6 Hz, the results look promising. The sensitivities determined using the mercury column agree with those determined using the oil column to within 2%. A typical waveform is shown in Figure 8.

It is planned to apply the full 55 MPa bias pressure to the oil

[3] See Reference 2

column in the next series of tests. The use of mercury will follow the successful conclusion of this experiment.

To use this modified version of the Earth's Field Dynamic Calibrator below 2 Hz (rps) will require a slower, geared down, motor to provide smooth operation; to operate above 8 or 10 Hz (rps) will require a better balancing system than the adjustable screw used in the end of the nonactive tube.

This appears to be the most promising technique for generating low frequency sinusoidal pressures and will be pursued further.

2.2.2 Extra Long Liquid-Filled Vertical Tube Calibrator

The maximum amplitude of the sinusoidal variations which can be generated by vertical tube technique depends on three parameters: liquid height, liquid density, and the acceleration amplitude to which the column can be subjected. The maximum acceleration amplitude is limited by the displacement capability of the electrodynamic vibration exciter used. Since acceleration amplitude is proportional to the product of the displacement and the square of the frequency, acceleration levels drop off rapidly with decreasing frequencies at constant displacement. The vibrator available for this task is limited to a maximum displacement of 1.27 cm peak-to-peak; this assumes that the weight of the calibrator can be compensated by a spring so that the table position of the vibrator can be centered within the mechanical limits of table displacement. For a 30.5-cm column of oil of specific gravity 0.86 the maximum peak-to-peak pressure variations which can be generated with this shaker range from about 73 kPa at 20 Hz to 4.6 kPa at 5 Hz.

Corresponding to the three constraints on generated pressure amplitude cited above, there are three ways of increasing this amplitude: (1) increasing displacement, (2) use of a liquid of greater density, and (3) use of a longer tube. We have used the last in a series of tests in which column length was increased by a factor of 4.5 to 137 cm. In this test water was used primarily as a convenience rather than for its slightly higher specific density, and the tube was not capped. The tube was vibrated on the elctrodynamic vibrator at frequencies ranging from 5 Hz to 20 Hz. A piezoresistive pressure transducer B-1 was used at the bottom of the tube and a static calibration was performed with the transducer in place by superimposing a pneumatic bias pressure of first 6.9 kPa and then-6.9 kPa. The average dynamic calibration value agreed with the static calibration value to within 1% and with the exception of one point the scatter of the sixteen data points was within 0.5%. The data are shown in the Table 4. It should be noted that at 5 Hz the generated pressure was 12.8 kPa peak-to-peak, about 2.8 times the pressure generated with the short tube. More careful centering of the vibration shake table allowing full use of the double displacement would increase the generated

pressure toward the theorectical 4.5 ratio in amplitude.

Calibrations were not performed below 5 Hz because of vibrator waveshape limitations; calibrations were not performed above 20 Hz because of the low, theoretical, 243 Hz column resonance and its effect on the amplitude frequency response.

2.2.3 Liquid Filled Tube with Generator of Large Sinusoidal Displacement

In Section 2.2.2 it was noted that in a liquid tube system, the range of generated pressure could be increased by larger shaker displacements. While there are commercially available shakers with displacements up to 30 cm, they are expensive, have a limited frequency range, and have long delivery dates. We decided to build a mechanical device that would impart a large, rectilinear, sinusoidal displacement to a liquid-filled tube. A 137-cm tube was constructed and mounted vertically using two air bearings (the tube weight was counterbalanced by an elastic cord). A motor with an eccentric was then used to drive the tube up and down by means of a connecting rod. Adjustment of the connecting rod on the eccentric wheel provided peak-to-peak displacements ranging from 5.1 cm to 11.4 cm in 1.27-cm increments. The upper bearing on the connecting rod was an air bearing; previous experience in developing the Earth's Field Dynamic Calibrator for Accelerometers [4] strongly suggested the use of air bearings to isolate the tube from motor-, gear- and bearing-vibration; mechanical vibrations transmitted to the liquid-filled tube create spurious pressures which are superimposed on the desired sinusoidal pressure.

At this stage of development the pressure signal generated is too noisy to be of use; when the motor was disconnected and the tube displaced by hand a clean signal was generated, verifying that the drive mechanism is creating the problem. Figure 14 shows a picture of the motorized calibrator; no data are shown because of the poor waveform obtained. Some efforts may be directed toward improving generated wave shapes, if, contrary to expectations, all the other approaches should prove to be unsuccessful.

2.2.4 Liquid Filled Tube on the Dual Centrifuge

The dual centrifuge developed for the calibration of accelerometers [5] was modified in an experimental set-up to calibrate pressure transducers. The centrifuge consists of a 61-cm diameter main turntable mounted in a horizontal plane and a second smaller turntable, 12.7 cm in diameter, mounted eccentrically on the larger turntable. By means of gears and belts, both turntables are constrained

[4] see reference 2
[5] see reference 3

to rotate at the same speed. The speed of rotation can be adjusted from 0.5 rps to 25 rps. The distance between the paralled shafts of the two turntables can be set to any value between 0 and 30.5 cm. The dual centrifuge was modified by attaching an oil-filled tube to the smaller turntable in a horizontal plane; this oil-filled tube, pressurized to 6.9 MPa, had a pressure transducer in one end and was capped at the other end. With the centrifuge in motion at constant speed the acceleration at the center of mass of the tube can be calculated from the square of the rotational speed and the distance of the center of mass from the center of rotation of the main turntable. From this the pressure seen by the transducer is calculate as with the vertical tube. The generated pressure is a maximum with the tube in a radial position with respect to the main turntable and the pressure transducer at the far end of the tube; 180 degrees later, with the tube again in a radial position but with the pressure transducer close to the center of rotation of the main turntable, the generated pressure is a minimum. Transducer C-1 was thus calibrated at rotational speeds from 2 rps to 6.5 rps (2 to 6.5 Hz). Figure 9 shows the waveform at 3 rps and 6 rps. Since the generated pressure is four times as great at 6 rps as it is at 3 rps, the signal to noise ratio is much more favorable at 6 rps; the noise is electrical in nature rather than vibrational. The calculated values of peak-to-peak pressure range from abour 9.0 kPa at 2 rps to 92.4 kPa at 6.5 rps.

The experimental data are given in Table 5. As in all other tests, the transducer sensitivity is computed by dividing the measured transducer output by the value of pressure calculated from acceleration, tube length and liquid density. Since the transducer response for this type is described by the manufacturer as being "down 3 dB at 1 Hz", the data were corrected fro this. If one assumes a simple RC roll-off, a response which is 3 dB (30%) down at 1 Hz will be down 1.4% at 6 Hz. The corrected experimental values were referred to the value measured at 6 Hz and the resulting curve plotted in Figure 10. Also shown is a theoretical curve for a system "down 3-dB at 1 Hz". Extrapolation of the curves suggests that the actual 3-dB frequency for this transducer system is close to 1.2 Hz.

It should be noted that experimental values of sensitivity obtained by this method were about 8% lower than those reported by the manufacturer. This discrepancy is still under investigation. Because of this and the more complicated test equipment, this technique is not likely to be as satisfactory as the use of the simple, vertical tube or the "windmill" technique.

2.3 Modified Double-Ended Piston-Cylinder Calibrator

Attempts to use a double-ended piston-cylinder calibrator were

[6] See Reference 1

described in the last report [6]. The concept appeared promising initially due to its ability to use the vibration exciter's blocked-motion power output at very low frequencies. Experimental data showed large discrepancies, which were thought due to remediable design flaws.

Accordingly a calibrator was designed and fabricated with four major modifications from the previous model:

(1) the clearance between the piston and cylinder was reduced from 2.54×10^3 cm to 2.54×10^4 cm;
(2) the piston and cylinder were made of steel, hardedned, and ground;
(3) the piston diameter was reduced from 3.81 cm to 1.27 cm;
(4) the "O" rings on the piston were eliminated.

A sketch of the modified device is shown in Figure 11 and a picture is shown in Figure 12.

The force exerted by the shaker on the yoke was measured by a load cell sandwiched between the yoke and the shaker head. The generated pressure was computed from the known diameter of the piston. Transducer A-3 was then mounted on the calibrator and a calibration attempted. The results were disappointing.

The waveform at all frequencies was poor; rotating the piston back and forth by hand radically improved the waveform suggesting that friction is still a problem. There were changes from 7% to 23% in transducer output, with load cell output and bias pressure held constant, at frequencies from 10 to 50 Hz. There were 17% to 46% changes in pressure transducer output when the load cell output and frequency were held constant, and the bias pressure was changed from 0.69 MPa to 6.9 MPa. There were 43% to 104% changes in pressure transducer output when the bias pressure and frequency were held constant and the load cell output was increased by 40%. The graph in Figure 13 shows the data. Even when frequency, bias pressure, and load cell output were held constant, the output of the pressure transducer measured at one minute intervals over a period of 15 minutes continuously increased. We have decided to abandon this approach to the dynamic calibration of pressure transducers since we have found more promising techniques (see 2.1.3 and 2.2.1).

3. Transducer Procurement

In the previous Progress Report we noted that a prototype pressure-sensing system using a semiconductor strain gage pressure transducer had been ordered in February 1973 with delivery expected in early August 1973. Delays in the receipt of materials and components by the manufacturer, have delayed delivery.

In May 1973, a contract was let for a prototype pressure sensing system using a variable-impedance transducer, and suitable for use

at high temperatures. This system was received in early September 1973. A cursory dynamic calibration showed the expected low output of about 1 mV for a 0.69 MPa peak-to-peak pressure fluctuation. Further evaluation was deferred, pending a static calibration of the system over the full range of bias pressures.

A semiconductor strain-gage pressure transducer was ordered in March 1973 with delivery promised for August 1973. The delivery date currently promised is for late November 1973.

Finally, in view of the satisfactory performance exhibited by the piezo-electric pressure transducers previously obtained, two additional ones were ordered. They were delivered early in September. They have not yet been tested.

4. Future Plans

We plan to calibrate all transducers by means of the liquid-filled vertical calibrator (see 2.1.3) in its latest version which permits simultaneous calibration of two transducers. We hope to use the "windmill" calibrator (see 2.2.1) for extending the low-frequency calibration capability, thus covering the entire frequency range of interest. When this has been accomplished at pressure amplitudes below the desired levels, we plan to use mercury or other high density fluids to extend the amplitude capability of the calibration technique.

Upon the successful demonstration of the capability of the "windmill" generator at high bias pressures, we expect to redesign and rebuild this device to meet the calibration objectives of this task.

A mathematical treatment of the capped tube amplitude-halving and frequency-doubling phenomena is being developed.

As soon as the dynamic pressure comparator in the NBS Cryogenic Metrology Division at Boulder is completed, we will send the previously evaluated transducers to that laboratory for tests at cryogenic temperatures.

5. References

1. Space Shuttle Pogo Pressure Measuring System, Progress Report for the period ending January 15, 1973, Report 135, Instrumentation Applications Section, NBS, February 15, 1973

2. Accelerometer Calibrations with the Earth's Field Dynamic Calibrator, NBS Technical Note 517, March 1970

3. A Dual Centrifuge for Generating Low Frequency Sinusoidal Accelerations, NBS Report #5730, 1958

T A B L E I

CALIBRATION OF TRANSDUCER A-3

Sensitivity at 50 Hz and Resonant Frequency Variation

From 6.89 MPa to 0.21 MPa (1000 psi to 30 psi)

Resonant Frequency Hz	Bias Pressure MPa	Bias Pressure psi	Transducer Output at ±10 g, mV rms
2227	6.89	1000	32.12
2224	6.21	900	32.28
2222	5.52	800	32.38
2217	4.83	700	32.46
2212	4.14	600	32.56
2208	3.45	500	32.60
2206	2.76	400	32.58
2200	2.07	300	32.52
2196	1.38	200	32.50
2193	0.69	100	32.42
2188	0.21	30	32.36
2233	6.89	1000	32.32

TABLE 2A

CALIBRATIONS OF QUARTZ CRYSTAL PRESSURE TRNASDUCERS

A-1

Bias Pressure MPa	#1 NBS Calib. 25 Hz mV/kPa	#2 NBS Calib. 25 Hz mV/kPa	#3 NBS Calib. 25 Hz mV/kPa	#1 NBS Calib. 50 Hz mV/kPa	#2 NBS Calib. 50 Hz mV/kPa	#3 NBS Calib. 50 Hz mV/kPa	#1 NBS Calib. 50 Hz mV/kPa	#2 NBS Calib. 100 Hz mV/kPa	#3 NBS Calib. 100 Hz mV/kPa
6.9	3.94	3.92	3.91	3.93	3.94	3.92	3.94	3.94	3.92
13.8			4.00			4.01			4.03
20.7			4.02			4.05			4.06
27.6	3.97	3.97	3.95	3.98	3.99	3.97	3.99	4.00	4.00
34.5			3.91			3.93			3.96
41.4			3.92			3.93			3.96
48.3			3.89			3.92			3.94
55.2	3.87	3.88	3.87	3.90	3.91	3.89	3.92	3.93	3.92

A-2

Bias Pressure MPa	#1 NBS Calib. 25 Hz mV/kPa	#2 NBS Calib. 25 Hz mV/kPa	#3 NBS Calib. 25 Hz mV/kPa	#1 NBS Calib. 50 Hz mV/kPa	#2 NBS Calib. 50 Hz mV/kPa	#3 NBS Calib. 50 Hz mV/kPa	#1 NBS Calib. 100 Hz mV/kPa	#2 NBS Calib. 100 Hz mV/kPa	#3 NBS Calib. 100 Hz mV/kPa
6.9	3.69	3.68	3.66	3.71	3.74	3.73	3.74	3.75	3.72
13.8			3.66			3.71			3.73
20.7			3.65			3.70			3.72
27.6	3.65	3.64	3.64	3.67	3.69	3.68	3.70	3.70	3.69
34.5			3.64			3.70			3.71
41.4			3.64			3.70			3.71
48.3			3.62			3.68			3.67
55.2	3.62	3.61	3.61	3.67	3.67	3.66	3.68	3.68	3.66

TABLE 2B

CALIBRATIONS OF QUARTZ CRYSTAL PRESSURE TRANSDUCERS

A-1

Bias Pressure psi	#1 NBS Calib. 25 Hz mV/psid	#2 NBS Calib. 25 Hz mV/psid	#3 NBS Calib. 25 Hz mV/psid	#1 NBS Calib. 50 Hz mV/psid	#2 NBS Calib. 50 Hz mV/psid	#3 NBS Calib. 50 Hz mV/psid	#1 NBS Calib. 100 Hz mV/psid	#2 NBS Calib. 100 Hz mV/psid	#3 NBS Calib. 100 Hz mV/psid
1000	27.2	27.1	27.0	27.1	27.2	27.1	27.2	27.2	27.0
2000			27.6			27.7			27.8
3000			27.7			27.9			28.0
4000	27.4	27.4	27.3	27.4	27.5	27.4	27.5	27.6	27.6
5000			27.0			27.1			27.3
6000			27.0			27.1			27.3
7000			26.9			27.0			27.2
8000	26.7	26.7	26.7	26.9	27.0	26.9	27.0	27.0	27.0

A-2

Bias Pressure psi	#1 NBS Calib. 25 Hz mV/psid	#2 NBS Calib. 25 Hz mV/psid	#3 NBS Calib. 25 Hz mV/psid	#1 NBS Calib. 50 Hz mV/psid	#2 NBS Calib. 50 Hz mV/psid	#3 NBS Calib. 50 Hz mV/psid	#1 NBS Calib. 100 Hz mV/psid	#2 NBS Calib. 100 Hz mV/psid	#3 NBS Calib. 100 Hz mV/psid
1000	25.4	25.4	25.3	25.6	25.8	25.7	25.8	25.8	25.6
2000			25.2			25.6			25.7
3000			25.1			25.5			25.6
4000	25.2	25.1	25.1	25.3	25.5	25.4	25.5	25.5	25.5
5000			25.1			25.5			25.6
6000			25.1			25.5			25.6
7000			24.9			25.4			25.3
8000	24.9	24.9	24.9	25.3	25.3	25.2	25.4	25.4	25.3

TABLE 3

HYDRAULIC SINUSOIDAL CALIBRATION
ESTIMATED CALIBRATION UNCERTAINTIES
PCB TRANSDUCERS AT $\pm$ 20 g, 50 Hz

Source of Error	Systematic Error Percentage of reading	Random Error Percentage of reading
Static Pressure		
Estimated error, height of liquid $\pm$0.08 cm, 30.5 cm	$\pm$0.26	
Estimated error in liquid density due to $\pm$2°C temperature variation, (petroleum oil, specific gravity 0.858)		$\pm$0.15
Acceleration		
Accelerometer sensitivity: 7.23 mV/g	$\pm$1.00	
Charge amplifier gain value	$\pm$1.50	
Noise:		$\pm$0.50
Output voltage: 2000 mV (manuf. value)		
Accuracy of calibration: $\pm$(0.05% reading + 0.05% range)	$\pm$0.30	
Repeatability + resolution, estimated $\pm$5mV		$\pm$0.25
Transducer output		
Output voltage: 70.00 mV		
Accuracy of calibration: $\pm$(0.05% reading + 0.05% range) manuf.	$\pm$0.12	
Repeatability + resolution, estimated $\pm$0.2 mV		$\pm$0.29
Estimated total systematic error rms=	$\pm$1.85%	
Estimated total random error, rms=		$\pm$0.65%
Estimated total error (S.E. + 3 R.E.)=$\pm$3.80%		

TABLE 4

DYNAMIC CALIBRATION OF PIEZORESISTIVE PRESSURE TRANSDUCER

B-1

USING A 137-cm WATER-FILLED TUBE

Frequency Hz	Generated Pressure kPa	psi	Transducer Sensitivity mV/kPa	mV/psi
5	12.8	1.86	1.19	8.21
6	15.6	2.26	1.18	8.11
7	18.3	2.66	1.17	8.07
8	21.2	3.07	1.17	8.05
9	23.9	3.47	1.17	8.04
10	26.8	3.88	1.17	8.05
11	29.5	4.28	1.17	8.06
12	32.4	4.70	1.17	8.04
13	35.2	5.11	1.17	8.04
14	38.1	5.52	1.17	8.06
15	40.7	5.91	1.17	8.09
16	43.6	6.32	1.17	8.07
17	46.3	6.71	1.17	8.09
18	48.9	7.09	1.18	8.12
19	51.5	7.47	1.18	8.12
20	53.9	7.82	1.18	8.11
			1.17 Average	8.08 Average

Static calibration 1.16 mV/kPa 8.0 mV/psi
System theoretical resonance frequency, 243 Hz

TABLE 5

CALIBRATION OF PIEZOELECTRIC
PRESSURE TRANSDUCER C-1 ON THE DUAL CENTRIFUGE

rps (Hz)	Transducer Output mV rms	Computed Pressure kPa peak-to-peak	psi	Sensitivity mV/kPa	mv/psi	Frequency Response %
2	16.6	0.88	1.28	532	36.7	86.9
2.5	27.2	1.37	1.99	561	38.7	91.6
3	40.07	1.98	2.87	573	39.5	93.6
3.5	55.00	2.69	3.90	578	39.9	94.5
4	72.60	3.52	5.10	584	40.3	95.4
4.5	93.20	4.45	6.45	593	40.9	96.9
5	115.5	5.49	7.96	595	41.0	97.3
5.5	140.7	6.64	9.63	599	41.3	98.0
6	168.5	7.90	11.46	603	41.6	98.6*
6.5	198.2	9.27	13.45	604	41.7	98.8

Note: This test was performed at a bias pressure of 6.9 MPa

*The value for 6 Hz is based on the manufacturer's data for frequency response.
Values at the other frequencies are relative to the 98.6% response at 6 Hz.

FIGURE 1 VIEW OF LIQUID FILLED TUBE DYNAMIC PRESSURE CALIBRATOR

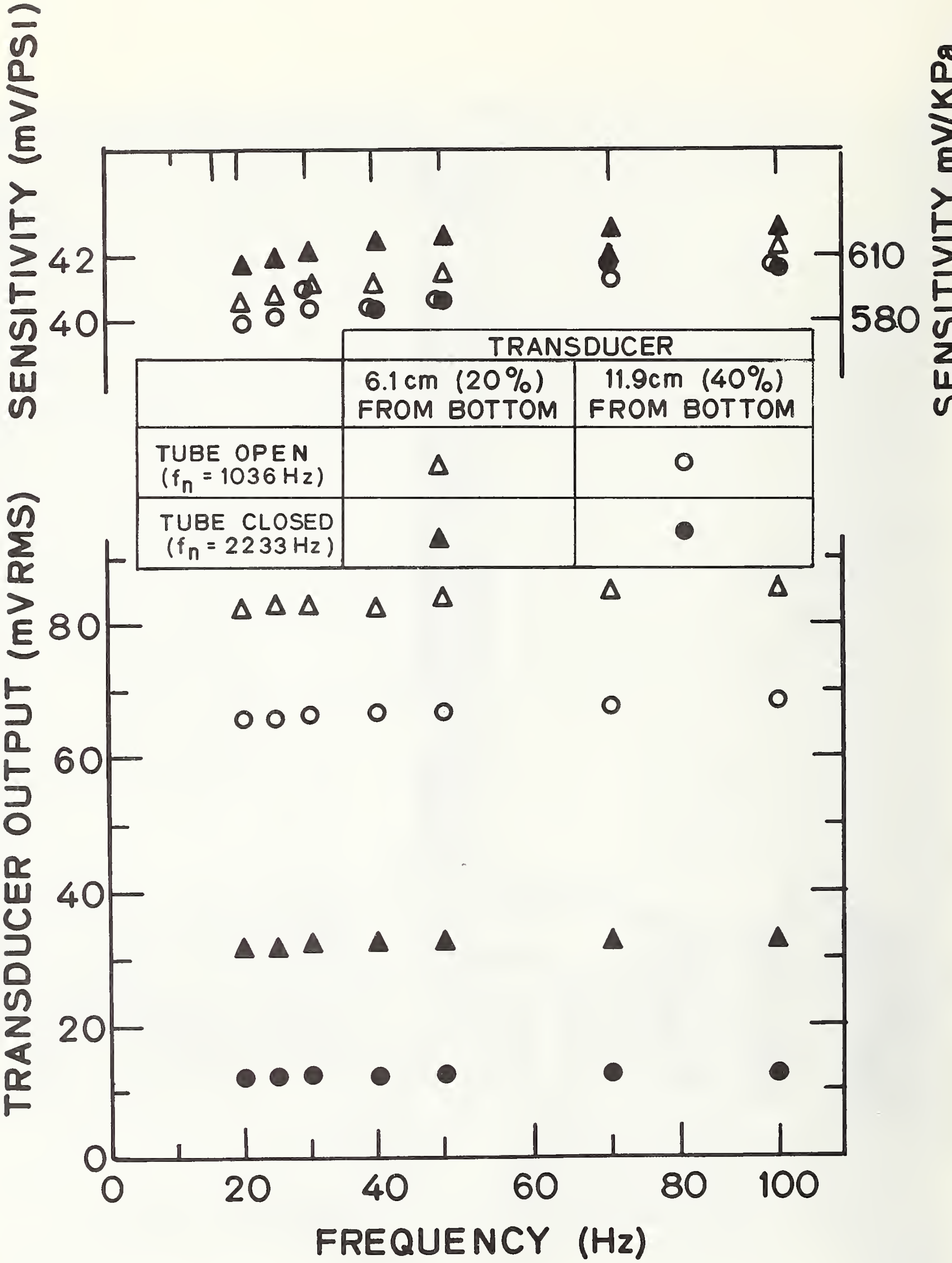


FIGURE 2: GENERATED PRESSURE AS A FUNCTION OF OPEN OR CLOSED TUBE AND OF TRANSDUCER POSITION

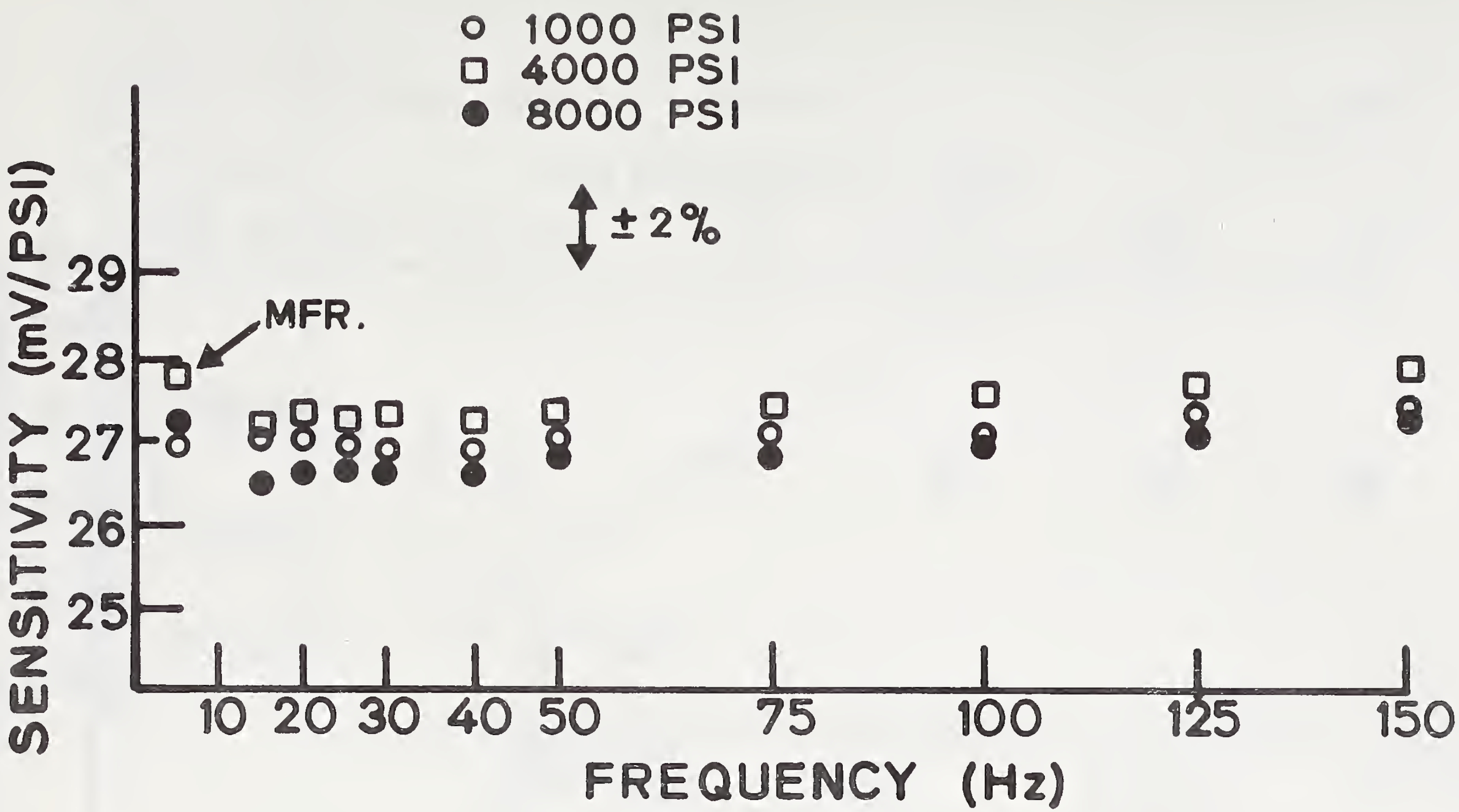


FIGURE 3: FREQUENCY RESPONSE OF TRANSDUCER A-1 AT THREE BIAS PRESSURES.

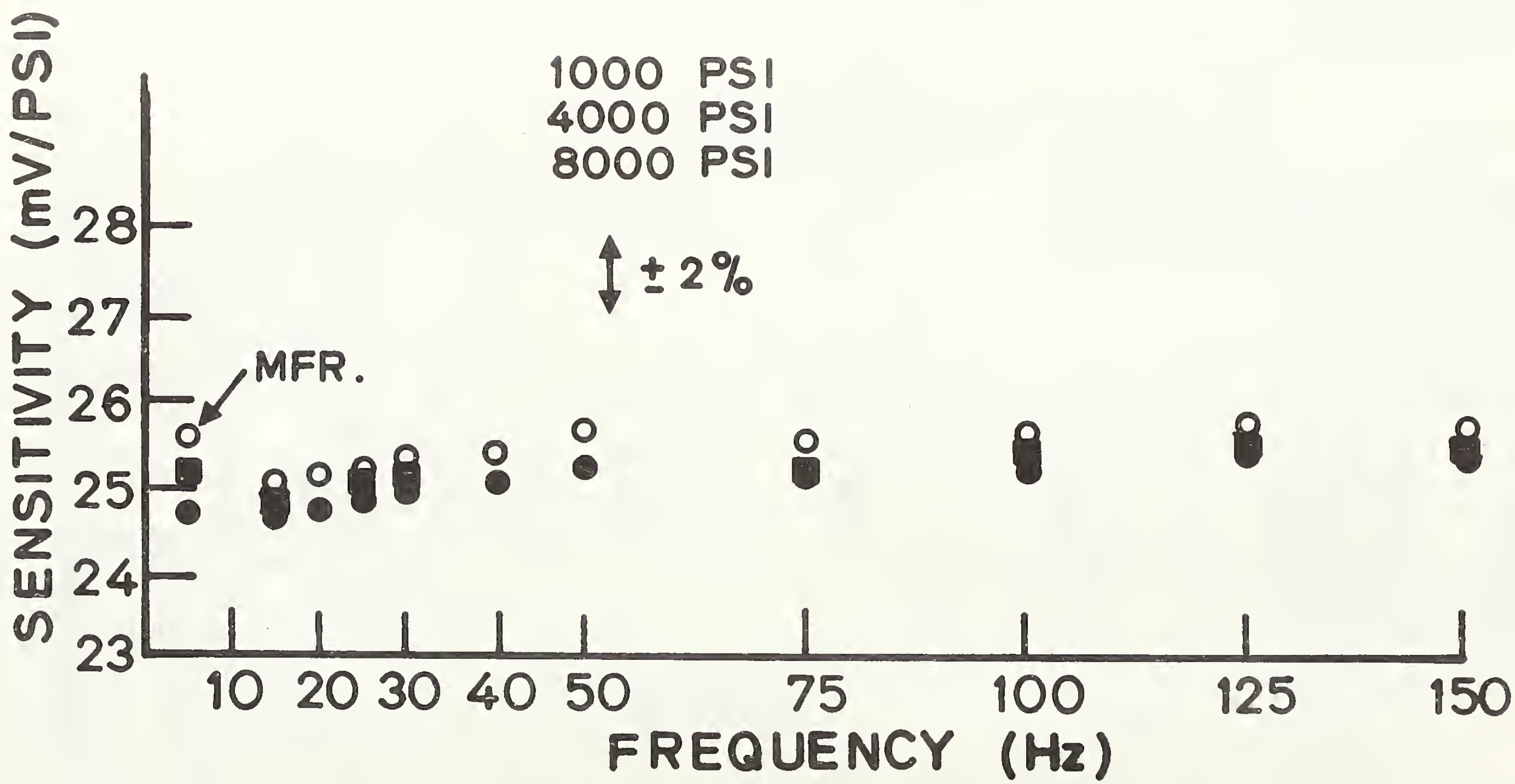


FIGURE 4: FREQUENCY RESPONSE OF TRANSDUCER A-2 AT THREE BIAS PRESSURES.

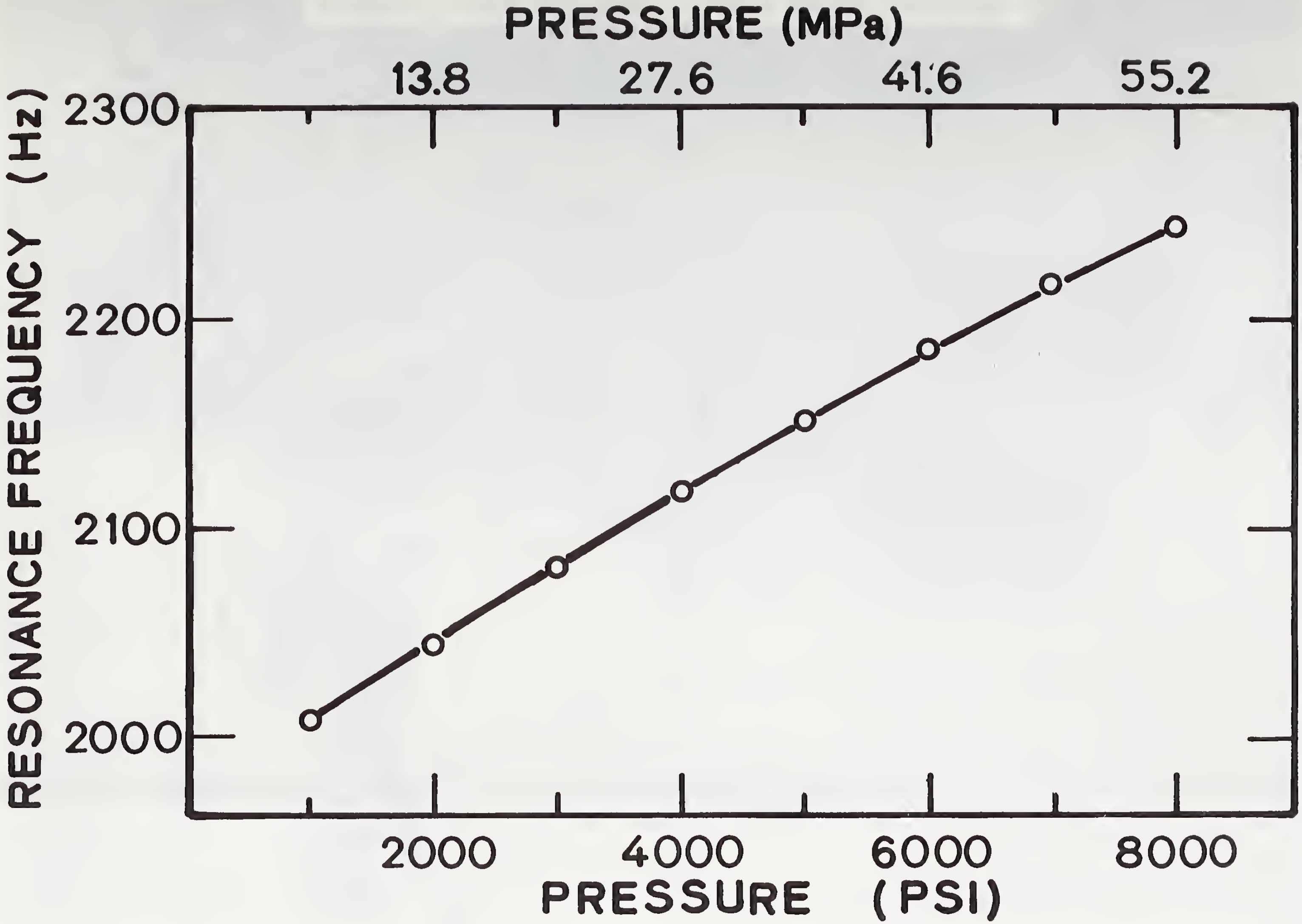


FIGURE 5: LIQUID FILLED VERTICAL TUBE CALIBRATOR, SYSTEM RESONANCE AS A FUNCTION OF BIAS PRESSURE

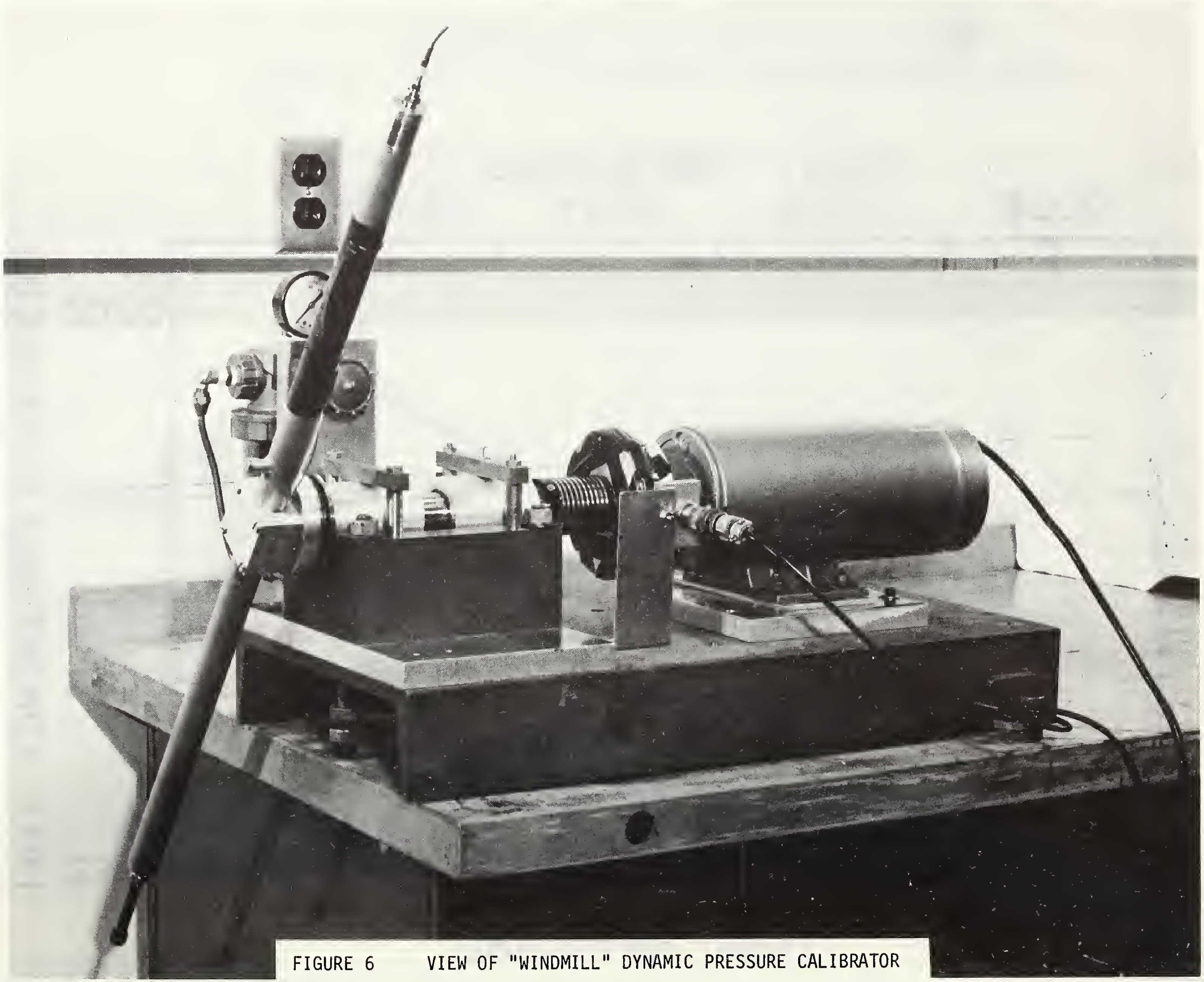


FIGURE 6 VIEW OF "WINDMILL" DYNAMIC PRESSURE CALIBRATOR

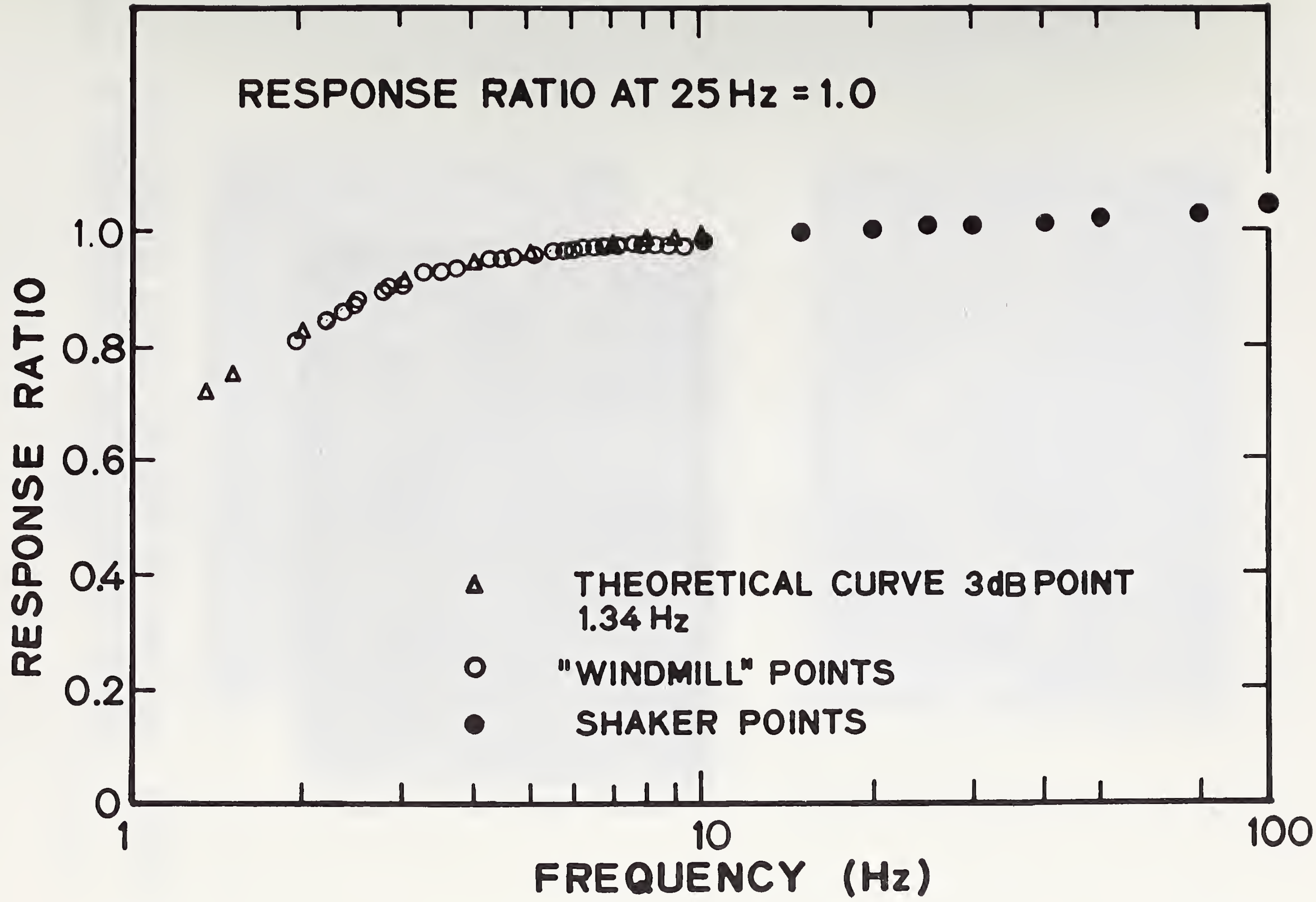
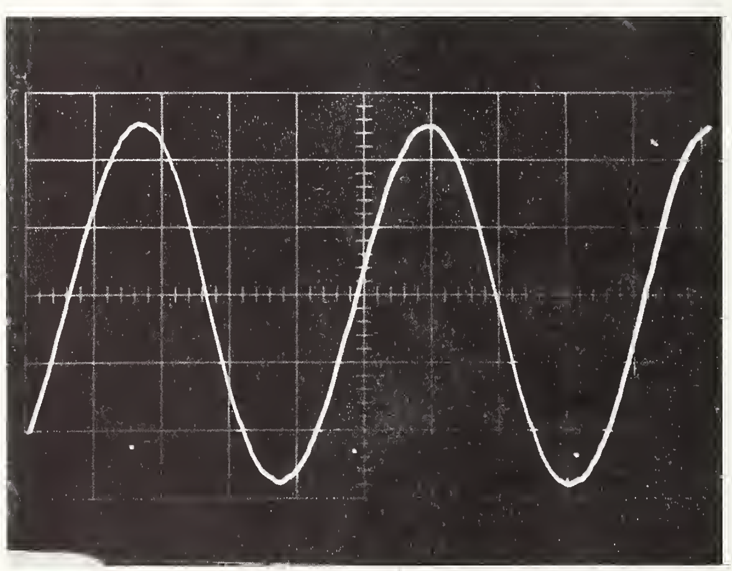


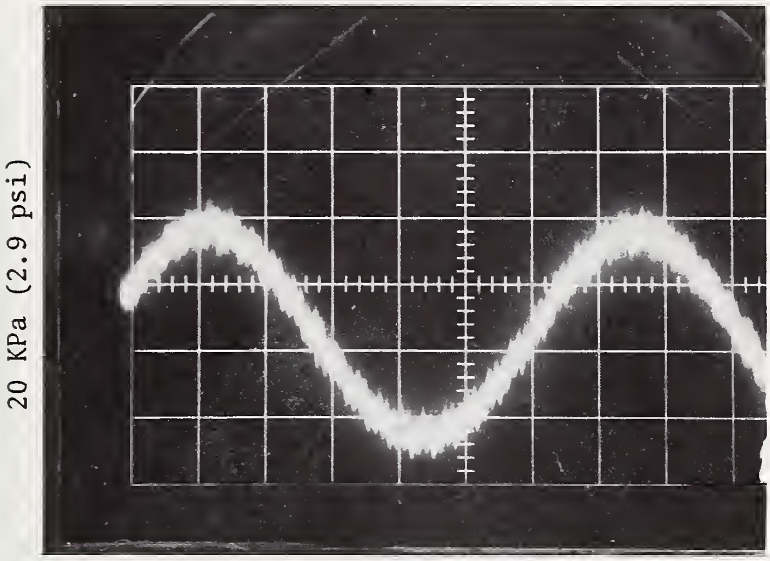
FIGURE 7: DYNAMIC CALIBRATION OF PIEZOELECTRIC PRESSURE TRANSDUCER BY TWO METHODS



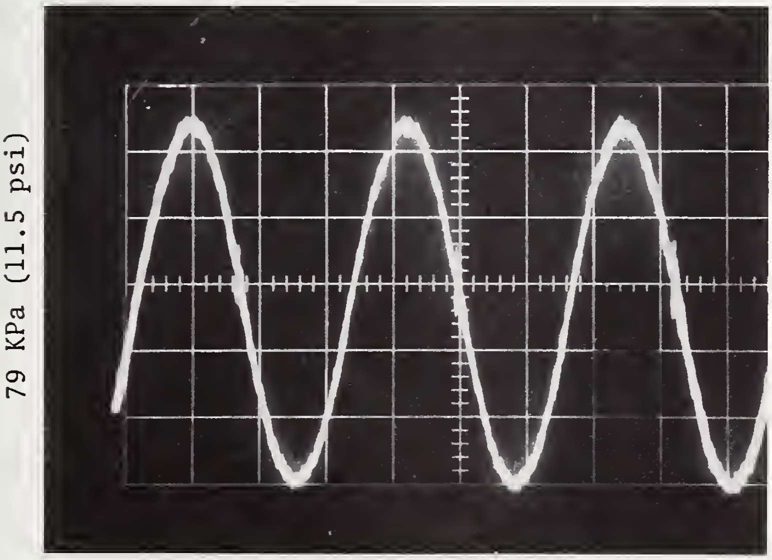
26 KPa (3.8 psi) peak-to-peak

5.4 Hz (5.4 rps)

FIGURE 8: WAVE SHAPE OF PRESSURE SIGNALS OBTAINED WITH MERCURY-FILLED "WINDMILL" PRESSURE GENERATOR



3 Hz (3 rps)



6 Hz (6 rps)

FIGURE 9 WAVE SHAPE OF PRESSURE GENERATED IN OIL FILLED TUBE ON DUAL CENTRIFUGE

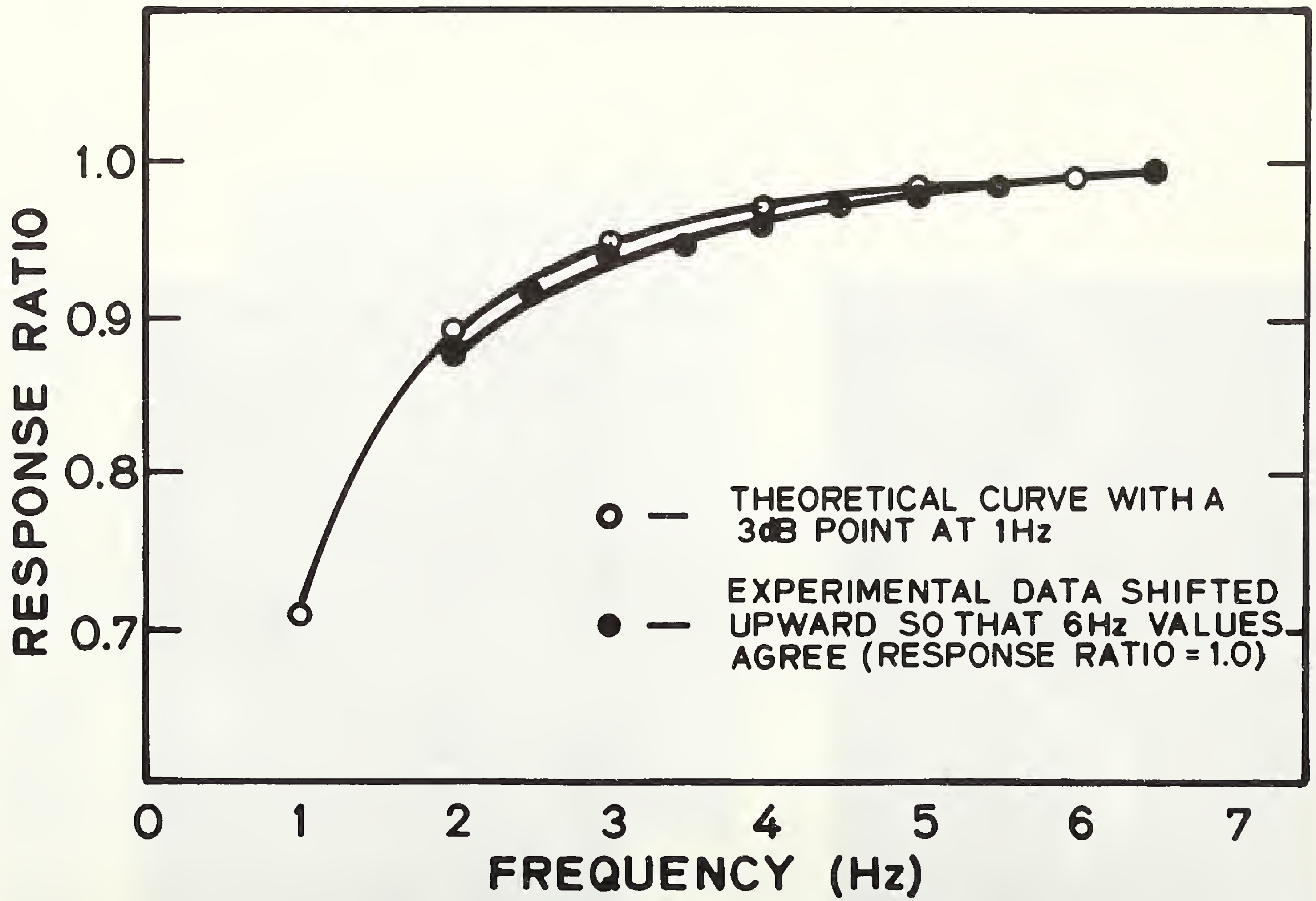


FIGURE 10: LOW FREQUENCY CHARACTERISTICS OF PIEZOELECTRIC PRESSURE TRANSDUCER OBTAINED BY USE OF DUAL-CENTRIFUGE PRESSURE GENERATOR

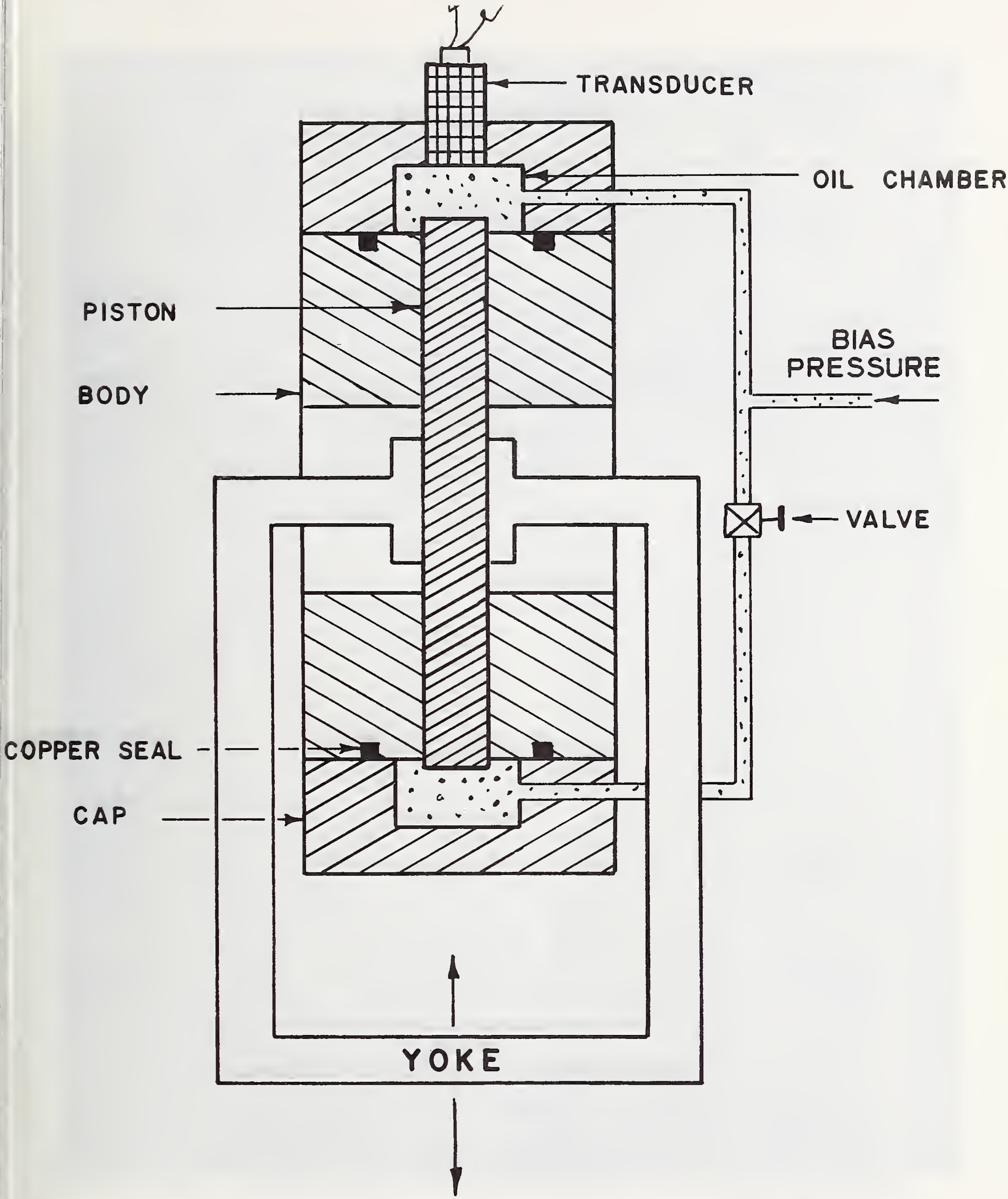


FIGURE 11: FUNCTIONAL DIAGRAM OF MODIFIED DOUBLE ENDED PISTON-CYLINDER DYNAMIC PRESSURE CALIBRATOR

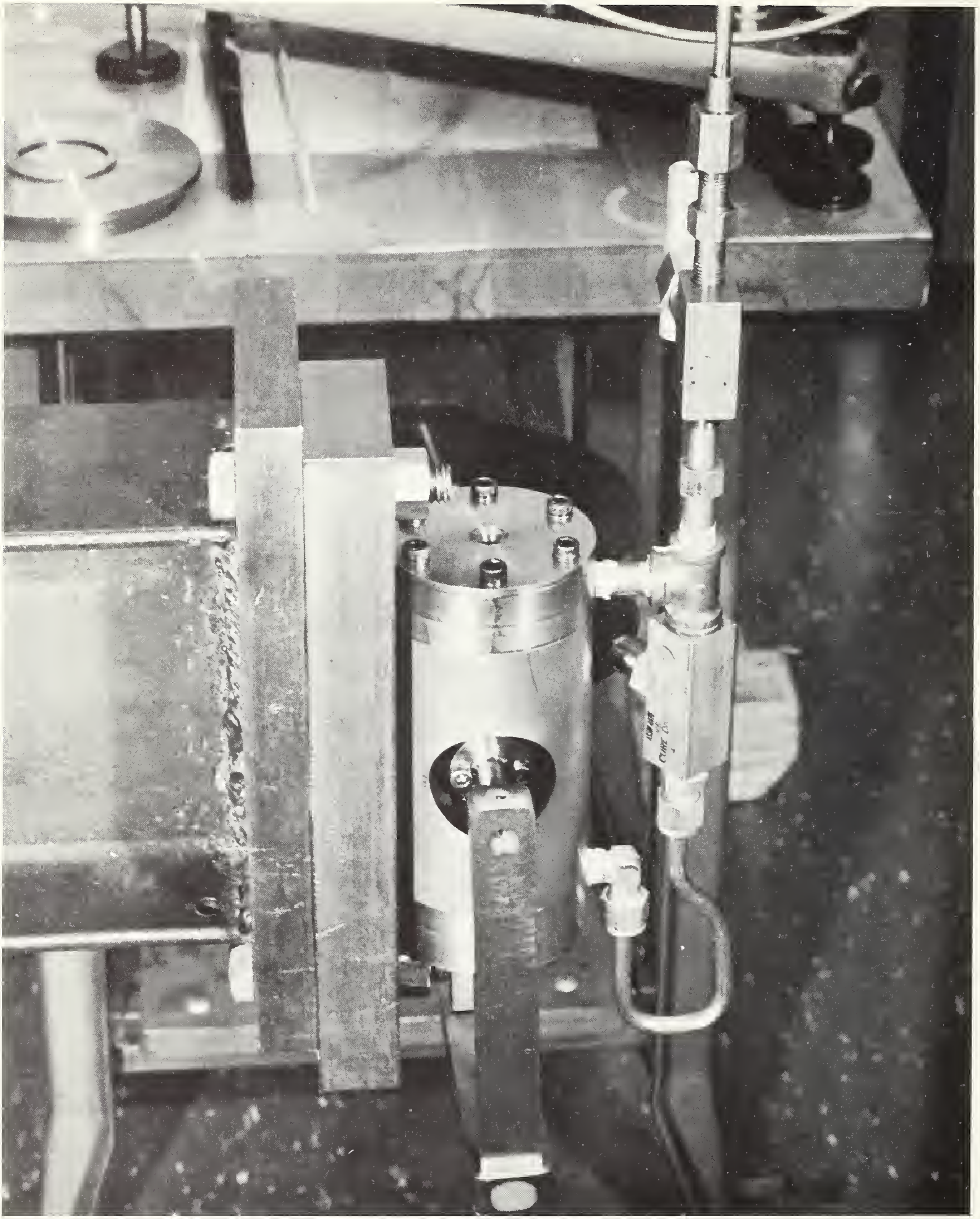


FIGURE 12: MODIFIED DOUBLE ENDED PISTON-CYLINDER DYNAMIC PRESSURE CALIBRATOR

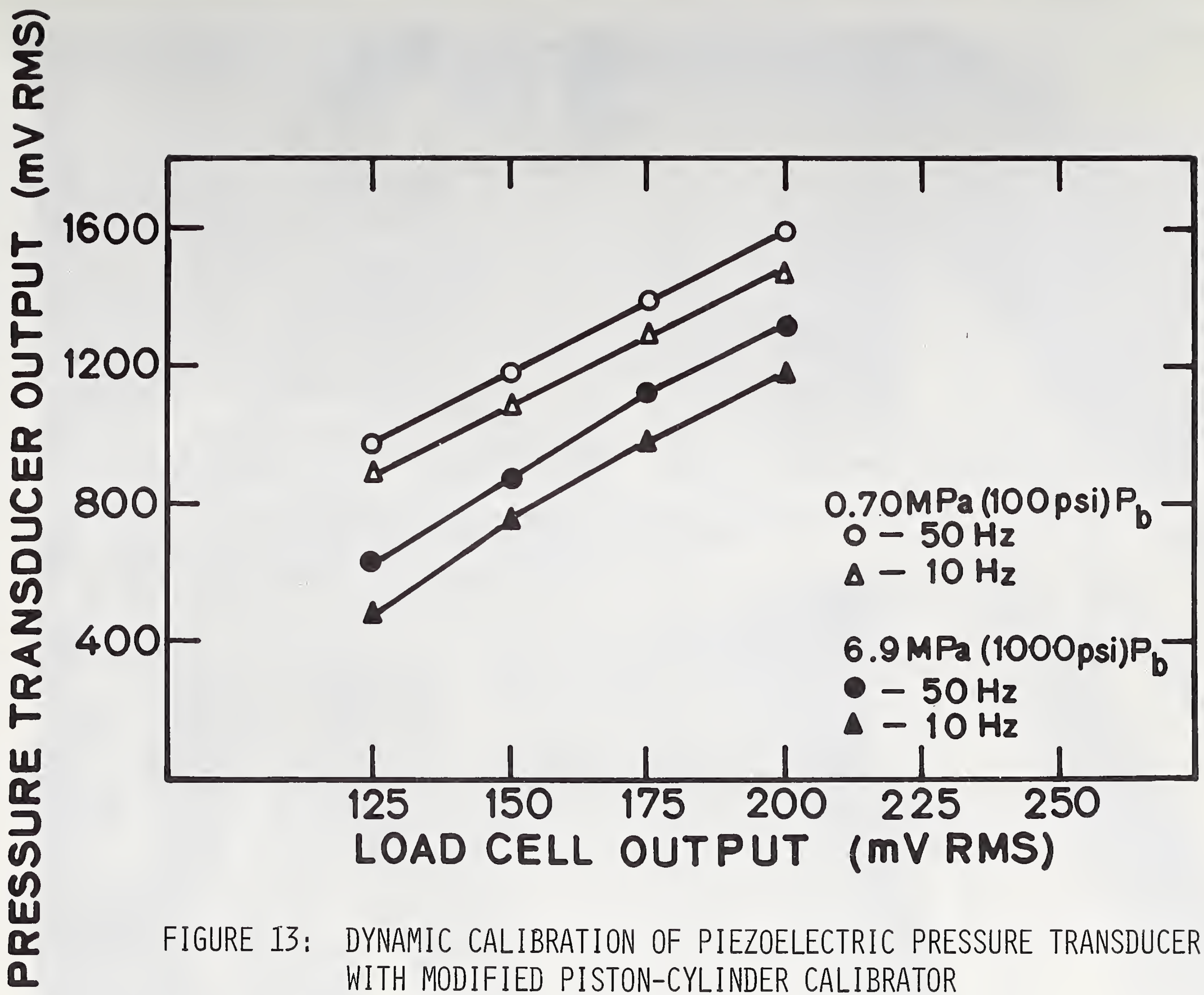


FIGURE 13: DYNAMIC CALIBRATION OF PIEZOELECTRIC PRESSURE TRANSDUCER WITH MODIFIED PISTON-CYLINDER CALIBRATOR

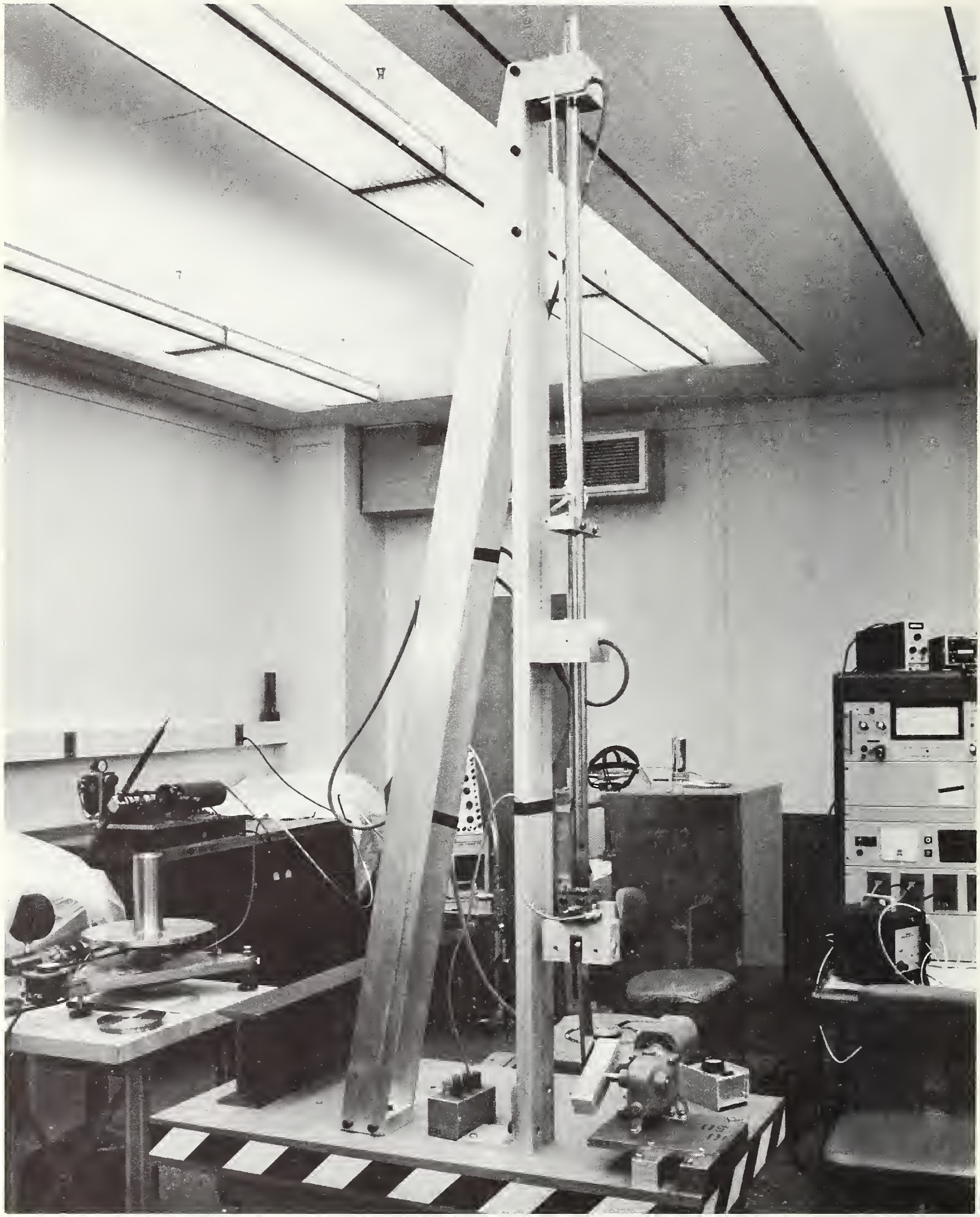


FIGURE 14: VIEW OF LIQUID FILLED TUBE ON MOTOR DRIVEN DISPLACEMENT GENERATOR

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This progress report describes a variety of experimental approaches to the dynamic calibration of pogo pressure transducers for the measurement of oscillatory pressures generated in the propulsion system of the space shuttle. The requirements are for the generation of a known (5% or better) sinusoidal pressure perturbation of 140 kPa (approx. 20 psi) peak-to-peak at bias pressures up to 55 MPa (approx. 8000 psi), over a frequency range from 1 Hz to 100 Hz. Vibrating a liquid column in a vertical plane is one technique developed that achieves 53 kPa (7.7 psi) peak-to-peak from 30 Hz to 150 Hz at all bias pressures, with smaller amplitudes at lower frequencies, reaching about 6 kPa (0.9 psi) peak-to-peak at 10 Hz. Another technique, rotating a liquid column in a vertical plane, shows promise at frequencies from 10 Hz down.

17. KEY WORDS *(six to twelve entries; alphabetical order, capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calibration; differential pressure; dynamic; high pressure; orbiter vehicle; pogo; pressure; sinusoidal; space shuttle; transducer.

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